On Exploring the Use of Mobility Parameters in the Analysis of Early Childhood Developmental Disorders

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***Abstract*— Impaired motor development is one of the initial signs of early childhood developmental disorders. Autism spectrum disorder (ASD), Cerebral Palsy (CP), and Attention Deficit Hyperactivity Disorder (ADHD) are the most common disorders that infants are affected in the USA. Albeit they are not being diagnosed until their school-age because there is no standardized clinical diagnosing routine like a blood test. Existing clinical diagnostic approaches are predominantly dependent on observational assessment by a trained physician along with patient feedback. Furthermore, these methods are subjective and do not provide an accurate decision. Nonetheless, research findings reveal that abnormal motor skills are often the initial signs of later developmental disorders. This paves the way for exploring alternative opportunities to identify the disease in the early stages of childhood. Recent advancements in sensing technologies facilitate convenient as well as unobtrusive methods to collect the mobility data even from the infants and be able to detect the disorder. Wearable devices are tiny and easy to use in collecting motor data from neonates and distinguish abnormal motor development from normal motor development. Thus, mobility data collection from an infant using a wearable sensor is beneficial in the early diagnosis of developmental disabilities like cerebral palsy. Our main contribution in this study is to present the analysis of various wearable sensor-based motor assessment methods in predicting childhood disorders. Furthermore, this document presents various crucial mobility parameters associated with identifying childhood disorders.**

Keywords- mobility; developmental disorder; wearable sensor;

I. INTRODUCTION

In recent years, the prevalence of developmental disorders among children is rising at an alarming rate. Early childhood developmental disorder is one of the primary causes for children being referred to primary healthcare clinics [1]. Chronic or perpetual delays in one or more motor functions of the child can be treated as a development disorder [2]. The onset of the disability may occur regardless of racial, ethnic, and socioeconomic groups. The manifestation of motor disability is caused by atypical brain development. Yet, specific reasons for atypical brain development are not known [3]. Research shows that preterm birth and pregnancy complications that occur in the perinatal period may affect the brain. Consequently, babies born in this category are at risk for neurodevelopmental impairments [4]. Additionally, low birth weight and infections during pregnancy are at high risk for several developmental disabilities. According to the study conducted by National Health Interview Survey (NHIS) in the United States, the growth of childhood disorders has increased to 17% between the years 2009 and 2017. Also, one out of six children between the age groups 3 and 17 years have one or more disabilities [6]. Furthermore, ADHD, ASD, and CP are the common disorders found among children and boys were more likely to be in the vulnerable group than girls [2].

The evolution of fine and gross motor skills in children with atypical neurodevelopment is cramped than children with typical neurodevelopment. As a result, affected children do not acquire smooth limb movements rather rigid and nonsynchronous [5]. Often, delays in acquiring sufficient motor movements are the early signs of later developmental impairment. Hence, an infant's motor assessment can be a potential parameter for the early diagnosis of the disability. Moreover, significant research is going on towards the assessment of an infant's motor function as a method to detect developmental disorders, such as cerebral palsy, autism [2][5][6]. The sooner the disorder is diagnosed the better the possibility for effective intervention therapy.

In the past decade, there has been a substantial rise in the quantitative assessment of motor dysfunction by attaching tiny sensors to neonates' upper and lower limbs. Abnormal movements are characterized by repetitive, stereotyped movements, rigid movements due to lack of smoothness, unusual gait patterns [4]. These atypical patterns are distinguishable by processing the mobility data collected from the sensors attached to a child's limb. Researchers have also concluded that abnormal movements are strongly correlated to their abnormal brain development [7]. The goal of motor assessment is to quantify the degree and range of motor disability and predict whether the child falls under the stage of Typical Development (TD) or At Risk (AR).

The primary purpose of this document is to review the various mobility assessment methods that were employed for diagnosing early childhood developmental disorders. At first subjective methods are discussed then wearable sensor-based assessment methods are elaborated. For this study, literature has been chosen which includes the following criteria.

1. The Data collected from human subjects by using wearable sensors
2. The primary aim of the article is to diagnose childhood disorders

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3. The motor movements are the main diagnostic assessment
4. The fundamental human subjects are infants or preschool-age kids.

The remaining sections of the document are structured as follows. In Section II, qualitative assessment methods are discussed. Section III explains the types of devices used for mobility data collection. The quantitative diagnostic approaches are presented in section IV. Under Section V, various aspects of mobility-based assessment methods are elaborated. Finally, Section V concludes with a summary of this work.

II. BACKGROUND

To discuss different assessment methods following three generalized developmental stages are defined.

A. Developmental Stages

At Risk (AR): Neonates born preterm and with pregnancy complications are considered At Risk (AR) of developing aberrant motor function and eventually likely to be diagnosed with developmental disorders including CP [2].

Typically developing (TD): Infants with normal limb movements are classified as Typical Developing (TD) [2].

Neurodevelopmental disorder (NDD): children who are already diagnosed with any developmental disorders like CP, ASD, and ADHD are categorized as infants with NDD [8].

According to the CDC [2], a TD child reaches certain developmental milestones as they grow. For instance, a 12-month-old toddler should be able to sit without any help and exhibit variable movements. On the other hand, AR infants lag in acquiring one or more such skills.

B. Qualitative Assessment Methods

Traditional assessment is heavily dependent on visual observation by a trained physician. Sometimes physicians prepare a questionnaire and assess the level of abnormality by integrating the feedback from the parents and/or the child. In such a scenario, parents might unaware of specific symptoms that the child is suffering, and the child may not be able to give precise feedback as adults. Hence, the decision-making becomes more complex. Additionally, existing clinical methods, such as analysis of neuroimaging require a trained consultant physician. But reliability and accuracy are largely depending on the expertise of the consultant. Besides the inherent complexity in judging the presence of the disorder, estimating the severity of the illness is far more challenging. The inception of qualitative assessment of the infant's nervous system is indeed a breakthrough in the diagnosis of developmental disorders.

The Alberta Infant Motor Scale (AIMS) [9] is one of the early observational scales to assess the neonate's gross motor function. In this method, a rating will be calculated based on the infant's performance in weight-bearing, posture, and antigravity movements. This method can be used only for babies under 18 months of age and the observer needs extensive training in the respective assessment. Prechtl et al. [10] proposed another observation-based systematic methodology termed General Movement Assessment (GMA) for diagnosing cerebral palsy. They have postulated that the quality of General Movements (GMs) is cramped and lacks smoothness over time due to impaired brain development. The absence of GMs may be observed from the video recording of an infant. This approach also does necessitate training by experts. In another experiment [11], Heineman et al. developed a video-based mobility evaluation technique, the Infant Motor Profile (IMP), that can differentiate between kids between TD and AR neurodevelopment. The downside of all these methods is that it involves an enormous human effort to examine the video recording for accurate prediction. Melbourne Assessment of Unilateral Upper Limb Function-2 (MA-2) is a standard reference tool to measure the quality of upper limb movements in kids with atypical brain growth aged between 2 to 15 years [12]. Moreover, scoring is estimated based on how a child performs 14 test activities including pickup and release of some objects.

Nonetheless, rating-dependent approaches have various shortcomings. (1) assessment is entirely observer-dependent. consequently, there is a high probability that the observer will make a wrong estimation. (2) Evaluation is time-intensive and consumes immense human effort. (3) The observer is required to be trained in advance with the necessary skills to make an optimal conclusion. After the training, it takes substantial time to acquire proficiency in the diagnosis. (4) Patients must visit the physicians and laboratories frequently. (5) Often, laboratories must have a specialized environment and equip with expensive tools. (6) monitoring the rehabilitation of the affected infants is challenging as there is a dependency on the observer. (8). Children's attention span is very limited, and so they can easily get annoyed with cumbersome instructions. Hence, it is essential to have an observer-independent approach with the best accuracy.

III. DATA AND DEVICES

Characterizing the atypical motor movements including repetitive and stereotypical patterns is crucial in the early diagnosis of neurodevelopmental disease. A qualitative examination of neonate movements necessitates a special skill set and the outcome varies from observer to observer [13]. To fill the gap, sophisticated systems, such as stereo photogrammetric movement analysis, gaze-tracking devices, and 3D motion tracking with passive markers [14] were introduced. Yet, these methods require an expensive structured setup with many wires and sensors to monitor the baby's physical movements. Wearable technology made it possible to collect the movement data by attaching tiny sensors to the body parts of the infants without major disturbance.

In recent times, Inertial Measurement Units (IMUs), also known as inertial sensors have been increasingly explored by numerous researchers. Typical IMUs comprise of

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accelerometer, gyroscope, and occasionally include a magnetometer. Nevertheless, many scholars have employed an accelerometer-based sensor to acquire infants' arm and leg movements [4][15][16]. Wearable instruments are suitable for monitoring the limb movements of infants because of their flexibility in sensor placement, adaptability, and power efficiency. Since the human subject is an infant, sensors are usually embedded in an appropriate peripheral, such as Leg warmers [7], wristwatches [17]. In some studies, skin-adhesive sensors have also been used [18]. Although the device has a variety of sensing technology, the aim is to collect the movement data unobtrusively without creating considerable discomfort to the babies. Therefore, wearable sensors are efficient for the objective assessment of children's movements. Fig. 1 depicts the convenient body locations where sensors are attached. And different impaired movements are shown that are characterized as aberrant motor movements exhibited by the disordered children.

Nowadays, wearable devices are compact yet affordable. They come with internal storage as well as a provision to connect and upload the data to cloud storage on the go. Most of the devices are battery-powered that eliminating the cumbersome wires and cables. When multiple sensors are included in the data collection process, then all the sensors must be actively synchronized throughout the duration. Then it allows collecting the data continuously from all the sensors even outside of the lab environment like home. Primarily, these devices are used to record upper and lower limbs that will help characterize the disorder.

IV. QUANTITATIVE ASSESSMENT

Measuring abnormality from the child's movements is an important clinical task as it reduces the significant human effort in identifying the impaired motor skills. Further, it helps physicians to come to an objective conclusion. With the latest advancements in wearable devices, it has become easy to attach them to infants and collect the data continuously. Various quantitative motor assessment studies are summarized in Table 1. This study includes the research that has employed wearable sensors and finds the quantitative measurement of the children's motor movements.

A few scholars had toiled and developed unobtrusive and non-invasive wearable instruments suitable for infants and toddlers. As early as 2008, Campolo et al. [14] prototyped a wearable sensing system for monitoring the upper and lower limb spontaneous movements of premature babies. Their sensing instrument can be used in infants as young as 2 weeks. They have hypothesized that abnormal movements are the early signs of later developmental disorders, such as autism. Redd et al. [18] carried a pilot project on a single healthy born infant to assess the General Movements (GMs) and Fidgety Movements (FMs) [10]. They have built a wearable monitoring system with an array of sensors to acquire the infant movements for both the short and long-term. Their results show that the absence of variability in GMs and FMs might be the early sign for the manifestation of neurodevelopmental disorders, such as CP. Nonetheless, they have experimented with only one healthy infant.

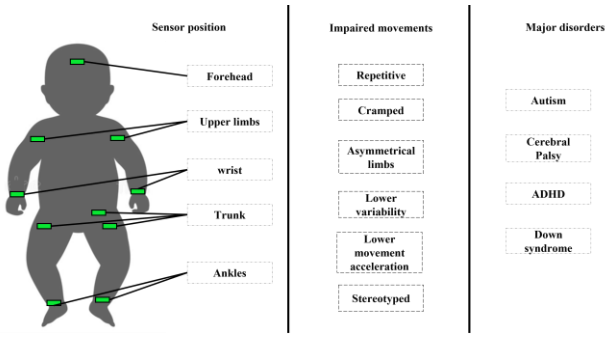

Figure 1: sensor-based quantitative diagnosis

Typically developing (TD) neonates demonstrate a rich and variable repertoire of movements compared to their counterpart infants at risk (AR) [19]. Often, it is critical to categorize between TD and AR during early infancy. Abrishami et al. [19] quantified infants' spontaneous leg movements by embedding tiny sensors inside custom-designed leg warmers. This study aimed to classify the group of infants into (TD) or (AR) from the day-long (8-13 hours) leg movements data. They also analyzed sensor data recorded from AR infants and were able to distinguish between AR babies with poor and good development. In [19], Goodfellow et al. developed binary classification algorithms to predict whether the child is TD or AR. In this approach, a group of 22 infants aged between 0 to 12 months was divided into two groups as 0-6 months and 6-12 months. Then, extracted two sets of features for each group and found a significant difference between TD and AR mobility data of 0-6 months than 6-12 months. Their findings prove the prominence of early childhood diagnosis.

Similarly, numerical estimation of abnormal mobility has also been studied in the past as it helps in distinguishing both, healthy and impaired. One of the early experiments demonstrated by Gravem et al. [4], utilized a simple accelerometer sensor and was able to collect the data from the premature neonates recruited from the NICU, who are potentially at risk of CP. Then, by extracting features and applying the machine learning technique including Decision Trees, he was able to recognize the abnormal movements namely Ccramped-Synchronized General Movements (CSGMs) [10]. According to Prechtl's assessment for CP [22], the presence of CSGM is an early marker for lateral developmental disorders. Wilson et al. [20], formulated Motion Complexity (MC) by measuring the variability from the infant's leg movement data. They conjectured that infants with lower MC are at risk (AR) of disabilities, such as ASD. Moreover, AR subjects compose lower motion complexity compared to TD subjects because their actions are repetitive and stereotyped. Smith et al. [15] proposed Sample Entropy (SampEn) as a function to measure the variation and repetition in kids' leg movements. Additionally, SampEn is lower for infants with developmental delays than normal infants. A different experiment carried by Hoyt et al. [17], assessed only upper limb movements and recommended two metrics: The Use

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TABLE 1: SUMMARY OF QUANTITATIVE METHODS

Reference	Purpose	Sensor	Sensor placement	Wear time (in hours)	Setting	Disorder	Movement type	Subjects	Age (in months)
[7]	Classify TD and AR	IMU	Ankles	8-13	Natural	NA	Spontaneous leg movements	12 TD 19 AR	1-15
[14]	Early diagnosis	IMU	Wrist and ankles	NA	Clinical	ASD	Spontaneous leg and arm movements	NA	NA
[19]	Classify TD and AR	IMU	Ankles	8-13	Natural	NA	Spontaneous leg movements	12 TD 19 AR	1-16
[20]	Diagnose ASD	IMU	Ankles	8-12	Natural	ASD	Spontaneous leg movements	5	3-12
[21]	Diagnose CP	Accelerometer	Ankles and wrist	20 min	Clinical	CP	Spontaneous leg and arm movements	19 TD 4 AR	<10
[18]	Diagnosis CP	IMU	Forehead, ankles, and wrist	1 min	Clinical	CP	Spontaneous head, leg, and arm movements	1 TD	3-5
[22]	Quantify leg movements	Inertial sensor	Ankles	8-13	Natural	NA	Spontaneous leg movements	12 TD	1-12
[4]	Predict impaired motor activity	Accelerometer	Head, ankles, and wrist	1	Clinical	CP	Spontaneous head, leg and arm movements	10 AR	<3
[23]	Number of days required for assessment	IMU	Ankles	5 days	Natural	NA	Spontaneous leg movements	16 AR	2-14
[15]	Measure variability of movements	IMU	Ankles	8-13	Natural	NA	Spontaneous leg movements	11 TD 20 AR	6-9
[24]	Assess leg movements	accelerometer	Right ankle	48 hrs. x 4 times	Natural	DS	Spontaneous right leg movements	8 TD 8 AR	3-6
[16]	Predict motor disorder	Accelerometer and gyroscope	Trunk, upper and lower limbs	4	clinical	CP, stroke	Predefined body movements	4 AR	9-12 years
[17]	Clinical vs motor assessment	Accelerometer	wrist	75	Natural	CP	Spontaneous upper arm movements	26 TD 26 AR	1-17 years

Ratio (UR) to measure the quality of using both arms and the Mono Arm Use Index (MAUI) for quantifying intensity and frequency of each arm. Their results signify that UR and MAUI are lower for typically developing children and higher for the children at of developmental delays.

Furthermore, many scientists are interested in studies specific to a particular disorder like cerebral palsy (CP) and Down Syndrome (DS). McKay et al. [24] conducted a mobility assessment of a group of infants with DS and without DS. Using an activity monitor attached to the baby's right ankle measured leg activity and sleep patterns at 3,4,5, and 6 months. Their statistical analysis observed a significant group difference between the infants with DS and without DS with respective to their motor component. Strohrmann et al. [16] acquired mobility data from four children (2 of them diagnosed with Cerebral Palsy and 2 others with stroke) who are undergoing rehabilitation. In this work, they were invited to perform a set of predefined motor tasks and measured the progress of the rehabilitation therapy using extracted features including smoothness in the upper and lower limb movements, and coordination between both arms. In another study conducted by Heinze. et al. [21], proposed an objective assessment methodology to diagnose cerebral palsy from the spontaneous leg and arm movements of newborn babies. Their method is built on a decision tree classifier algorithm and achieved ~90% accuracy. Further, they have posited that their methodology can be easily adapted by the clinical practitioners and helps to monitor the progress of rehabilitation.

A different experiment performed by Deng et al. [23] assessed the motor behavior of neonates to determine the minimum number of days required to characterize the ideal daily leg movement patterns of children who are at risk of developmental disorders. They hypothesized that two days of leg movement data is sufficient to accurately predict developmental disorder among the infants at risk. Smith et al. [22] developed an algorithm to measure the full day leg activity and attempted to identify the relationship between the number of leg movements and the onset of walking. However, their test produced surprisingly unexplainable results as infants with a smaller number of leg movements began walking early than the babies with a greater number of leg movements.

V. DISCUSSION

This section presents the various aspects of mobility-based assessment approaches and discusses their merits as well as demerits.

A. Challenges in Data Collection

Infants motor assessment using wearable sensors have been increasing over the last decade because of its miniature size and wearability. Also, sensors can be attached to any part of the body and have the capability to work in a laboratory setting as well as in a home environment. Nonetheless, unlike adults collecting data from kids is not so easy for various reasons. (1) Preparing an infant for data collection is challenging because they are fragile and need utmost care. If it is a lab environment, then room temperature must be adjusted to the comfort of the child [21]. Additionally, the parent must ensure essential daily routines, such as breastfeeding and diapering. So, the child is ready and perform desired spontaneous movements (2) Children's behavior is unpredictable, so sensors may drop off or loosen which can eventually add noise in the data stream. For this reason, in a clinical setting or home environment, either a parent or a caregiver must always be present to take care of sensor positing during the data acquisition period [23][25]. (3) size and sensor placement are important to lessen the irritation to the child. From the ongoing research, it is evident that the average weight of each sensor ranges between 10 grams to 30 grams [7][17][18]. However, the sensor's positioning has limited choices as it needs to be placed on the arms and legs to measure the limb movements.

B. Wear Time

Although there is no evidence for precise sensor wear time required for accurate data analysis, numerous studies collect the data for more than one hour for an objective conclusion. As wearable technology is advancing, it is now possible that sensors can be placed in diversified products like leg warmers [7] which are comfortable for the infant. Hence, some scholars have embedded sensors in the form of socks, wristwatches and were able to collect the data for 2 to 5 days. Nonetheless, according to the study conducted by Deng et al. [23], two days of sensor data of infants is sufficient to differentiate between typical and atypical movements pattern. Yet, further investigations are necessary to minimize the wear time.

C. Accuracy and Validation

Accuracy validation of an infant's motor assessment method is crucial for decision-making in clinical research. Irrespective of the methodology used for the assessment, it is essential to compare the results with ground truth to measure the accuracy of the model. Researchers are primarily depending on two types of accuracy validation approaches for the context of an infant's motor assessment. Each method differs by ground truth. (1) In this approach, the sensor data collection procedure is video recorded such that normal and abnormal movements are annotated by experts. This annotated data is used as ground truth to validate the accuracy [7][15][16][17][22]. Undoubtedly, it is one of the popular and fastest methods used in many studies. (2) As an alternative, some investigators do the follow-up of the infant's health status after a few months to validate their inference, of those who were classified as high risk. In a study done by Wilson et al. [20], the authors assessed children's movement complexity pattern at 3,6, 9, and 12 months of age, however, follow-up was done at 18 and 36 months of age to validate their results.

D. Noise Elimination

Unfortunately, infant movement data recorded from the sensors is mostly accompanied by noise [22]. Especially, in the context of infants, the amount of noise-induced might be higher than normal. Because the daily routine of every child frequently changes between sleep, waking, and active states. Besides, a child might experience discomfort for unknown reasons. Then, either parent or caregiver must pacify the child to resume the data recording. Thus, the presence of noise is inevitable in children's movement data. Due to the effects of noise, movement assessment derived from the noisy sensor data is biased and inaccurate. To eliminate the noise from the movement data, investigators have employed different techniques. To eliminate outliers, preprocessing and normalization of the data are some of the popular approaches [11][16][22]. In this approach, raw data is normalized and standardized to align within either first or third quantiles. Alternatively, parents or caregivers to write down the activity log of any major change in movement [7][15]. For instance, the activity log records the sleep, wake, and play times of the child. This method helps to extract the data which is relevant and useful based on the activity log.

E. Quantifiable Parameters

Quantitative measurement has been used by several researchers for the automatic assessment of impaired motor function. In contrast, some researchers have developed a quantifiable metric that can measure the level of motor impairment. Their main objective is to quantify variability and repeatability of arm and leg movements as a unit that can be used to measure the degree of neuromotor control. Wilson et al. [20] proposed an objective metric called Motion Complexity (MC) from the full-day mobility data acquired from the sensors attached to both legs. MC is computed from the duration of movement, peak acceleration, and average acceleration during a movement. MC is essentially a measure of the variability of the recorded leg movements. Their experimental results demonstrate that two kids from the sample of five subjects, have lower MC scores than the other three kids and they later developed ASD. Sample Entropy (SampEn) is another quantitative measure introduced by smith et al. [15]. Their analysis proved that AR infants' SampEn values are significantly lesser than TD infants. Hence, SampEn may be a potential early marker to detect abnormal growth of neuromotor control. Hoyt et al. [17] computed two metrics from the sensor data of upper limb movements: Use Ratio (UR) and mono arm use index (MAUI). These two components measure the asymmetry between the two arms. They postulated that infants with neurodevelopmental deficits might not use both arms like normal children. Their study results corroborated their theory.

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F. Spontaneous Movements vs Therapeutic Movements

While spontaneous movements are either leg or arm movements recorded during an infant's active playtime, therapeutic (pre-defined) movements are designed by researchers in collaboration with clinical expert physicians [16]. Pre-defined movements are straightforward to process because they are logged in a well-controlled lab environment and accurate movement is well known in advance. Whereas spontaneous movements require additional processing to extract useful features as well as suppress unnecessary noisy data [21][22]. Although pre-defined movements processing technique is simple to use, scholars are mostly interested in spontaneous physical movements. Because the treatment of spontaneous arm and leg movements is more practical and accurate.

VI. Conclusion and Future work

Developmental disorders such as autism hamper the typical behavior of a child. Consequently, they do not grow like a normal child. Thus, it is crucial to diagnose and begin the treatment as soon as early infancy. However, the most frequently used clinical method is ineffective in the early detection of the disorder. Quantitative measurement of disability using smart wearable devices speeds up the diagnosing process. This document highlighted the importance of quantitative prognosis and presented the various diagnostic approaches that are explored by the scientific community as a method of identifying the disorder by employing sensor devices.

References

[1]. K. A. I. Evensen, S. Sellæg, A.-C. Stræte, A. E. Hansen, and I. Meisingset, "Profile of children referred to primary health care physiotherapy: a longitudinal observational study in norway," BMC Health Services Research, vol. 21, no. 1, pp. 1–10, 2021.

[2]. Centers for Disease Control and Prevention, "Developmental disabilities," 2021, [Online; retrieved: October 2021]. Available from: https://www.cdc.gov/ncbddd/developmentaldisabilities/index.html

[3]. B. Zablotsky et al., "Prevalence and trends of developmental disabilities among children in the United States: 2009–2017," Pediatrics, vol. 144, no. 4, e20190811,2019.

[4]. D. Gravem et al., "Assessment of infant movement with a compact wireless accelerometer system," Journal of Medical Devices, vol. 6, no. 2, 2012.

[5]. F. Ferrari et al., "Cramped synchronized general movements in preterm infants as an early marker for cerebral palsy," Archives of pediatrics & adolescent medicine, vol. 156, no. 5, pp. 460– 467, 2002.

[6]. L. Meinecke et al., "Movement analysis in the early detection of newborns at risk for developing spasticity due to infantile cerebral palsy," Human movement science, vol. 25, no. 2, pp. 125–144, 2006.

[7]. M. S. Abrishami et al., "Identification of developmental delay in infants using wearable sensors: Full-day leg movement statistical feature analysis," IEEE journal of translational engineering in health and medicine, vol. 7, pp. 1–7, 2019.

[8]. I. Braito et al.,"Assessment of upper limb use in children with typical development and neurodevelopmental disorders by inertial sensors: a systematic review," Journal of neuroengineering and rehabilitation, vol. 15, no. 1, pp. 1–18, 2018.

[9]. M. C. Piper, L. E. Pinnell, J. Darrah, T. Maguire, and P. J. Byrne, "Construction and validation of the alberta infant motor scale (aims)." Canadian journal of public health= Revue canadienne de sante publique, vol. 83, pp. S46–50, 1992.

[10]. C. Einspieler and H. F. Prechtl, "Prechtl's assessment of general movements: a diagnostic tool for the functional assessment of the young nervous system," Mental retardation and developmental disabilities research reviews, vol. 11, no. 1, pp. 61–67, 2005.

[11]. K. R. Heineman, A. F. Bos, and M. Hadders-Algra, "The infant motor profile: a standardized and qualitative method to assess motor behaviour in infancy," Developmental Medicine & Child Neurology, vol. 50, no. 4, pp. 275–282, 2008.

[12]. M. Randall, C. Imms, and L. Carey, "Establishing validity of a modified melbourne assessment for children ages 2 to 4 years," American Journal of Occupational Therapy, vol. 62, no. 4, pp. 373–383, 2008.

[13]. H. Chen, M. Xue, Z. Mei, S. Bambang Oetomo, and W. Chen, "A review of wearable sensor systems for monitoring body movements of neonates," Sensors, vol. 16, no. 12, p. 2134, 2016.

[14]. D. Campolo et al., "A novel technological approach towards the early diagnosis of neurodevelopmental disorders," in 2008 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE, 2008, pp. 4875–4878.

[15]. B. A. Smith, D. L. Vanderbilt, B. Applequist, and A. Kyvelidou,"Sample entropy identifies differences in spontaneous leg movement behavior between infants with typical development and infants at risk of developmental delay," Technologies, vol. 5, no. 3, p. 55, 2017.

[16]. C. Strohrmann et al., "Monitoring motor capacity changes of children during rehabilitation using body-worn sensors," Journal of neuroengineering and rehabilitation, vol. 10, no. 1, pp. 1–16, 2013.

[17]. C. R. Hoyt et al.,"Using accelerometry for measurement of motor behavior in children: Relationship of real-world movement to standardized evaluation," Research in developmental disabilities, vol. 96, p. 103546, 2020.

[18]. C. B. Redd, L. A. Barber, R. N. Boyd, M. Varnfield, and M. K.Karunanithi, "Development of a wearable sensor network for quantification of infant general movements for the diagnosis of cerebral palsy," in 2019 41st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC). IEEE, 2019, pp. 7134–7139.

[19]. D. Goodfellow et al., "Predicting infant motor development status using day long movement data from wearable sensors," arXiv preprint arXiv:1807.02617, 2018.

[20]. R. B. Wilson, S. Vangala, D. Elashoff, T. Safari, and B. A. Smith, "Using wearable sensor technology to measure motion complexity in infants at high familial risk for autism spectrum disorder," Sensors, vol. 21, no. 2, p. 616, 2021.

[21]. F. Heinze et al., "Movement analysis by accelerometry of newborns and infants for the early detection of movement disorders due to infantile cerebral palsy," Medical &

biological engineering & computing, vol. 48, no. 8, pp. 765–772, 2010.

[22]. B. A. Smith, I. A. Trujillo-Priego, C. J. Lane, J. M. Finley, and F. B. Horak, “Daily quantity of infant leg movement: wearable sensor algorithm and relationship to walking onset,” Sensors, vol. 15, no. 8, pp. 19 006–19 020, 2015.

[23]. W. Deng, I. A. Trujillo-Priego, and B. A. Smith, “How many days are necessary to represent an infant’s typical daily leg movement behavior using wearable sensors?” Physical therapy, vol. 99, no. 6, pp. 730–738, 2019.

[24]. S. M. McKay and R. M. Angulo-Barroso, “Longitudinal assessment of leg motor activity and sleep patterns in infants with and without down syndrome,” Infant Behavior and Development, vol. 29, no. 2, pp. 153–168, 2006.

[25]. N. Jalloul, “Wearable sensors for the monitoring of movement disorders,” Biomedical journal, vol. 41, no. 4, pp. 249–253, 2018.

 ISBN: 978-1-61208-917-1